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The Quest for the Sun's Siblings: an Exploratory Search in the Hipparcos Catalogue

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ABSTRACT
We describe the results of a search for the remnants of the Sun's birth cluster among stars in the Hipparcos Catalogue. This search is based on the predicted phase space distribution of the Sun's siblings from simple simulations of the orbits of the cluster stars in a smooth Galactic potential. For stars within 100 pc the simulations show that it is interesting to examine those that have small space motions relative to the Sun. From amongst the candidate siblings thus selected there are six stars with ages consistent with that of the Sun. Considering their radial velocities and abundances only one potential candidate, HIP 21158, remains but essentially the result of the search is negative. This is consistent with predictions by Portegies Zwart (2009) on the number of siblings near the Sun. We discuss the steps that should be taken in anticipation of the data from the Gaia mission in order to conduct fruitful searches for the Sun's siblings in the future.

Key words: Sun: general – Galaxy: kinematics and dynamics, solar neighbourhood – Solar system: formation

1 INTRODUCTION

The Sun's life history has long been a subject of interest not just in astrophysics but also in fields such as solar system studies, the history of the earth's climate, and understanding the causes of mass extinctions. The possible birth environment of the Sun was discussed extensively by Adams (2010) who shows how inferences about this environment can be made by considering its impact on the formation and morphology of our planetary system, the removal of the solar nebula, and the presence of short-lived radioactive nuclei in meteorites. The subsequent life and times of the Sun as it travels through our Galaxy have attracted attention in the context of trying to understand climate change and mass extinctions as the consequences of astronomical impacts. The evidence for and against this idea was reviewed by Bailer-Jones (2009), who points out problems in the methodology of the various studies into climate change or mass extinctions and also the uncertainties in the details of the Sun's path through our Galaxy even over the past 545 Myr.

As discussed by Portegies Zwart (2009) the Sun is likely to have been born in a bound open cluster consisting of a few thousand stars. This cluster probably had a radius of a few pc and as pointed out by Adams (2010) the Sun was located not too far from the cluster centre ($\sim$ 0.2 pc) as inferred from the necessity of a nearby supernova explosion. The fact that the Sun thus has a large 'family' prompted Portegies Zwart (2009) to ask the question: can we find the Sun's siblings? The answer to this question is important as the inferences about the Sun's birth environment all come from considering the Sun and its planets, there is as yet no direct observational constraint on the birth cluster itself. Identifying even a small number of the Sun's siblings would put constraints on the number of stars in the cluster, by extrapolation for a plausible IMF, and possibly even on the IMF itself if siblings were found over a range of stellar masses. Reconstructing the orbits of the siblings in the Galaxy would lead to a more accurate determination of the Sun's birth location as well as the subsequent path to its present day position. This information could be used, for example, to investigate whether the Sun's relatively high metallicity (cf. Adams 2010) can be explained by its birth at a different radius in the Galaxy. In addition we would obtain a determination of the Sun's motion through the Galaxy independent from the geological record, which was listed by Bailer-Jones (2009) as an important goal for the study of the history of the earth's climate and mass extinctions. Portegies Zwart (2009) proceeded by considering the constraints on the Sun's birth cluster and performing simple simulations of the evolution of a cluster of stars initially confined to a 1 pc virial radius and orbiting our Galaxy along the presumable path the Sun followed in the past. Depending on how quickly the cluster became unbound Portegies Zwart (2009) concluded that $\sim$ 10–40% of the Sun's siblings should still be located with 1 kpc of the present day location of the Sun.

Thus we can expect to find about $\sim$ 100–1000 of the Sun's siblings with 1 kpc from the present day position of the Sun. This will make a search for the siblings extremely challenging as they will have to be weeded out from among the $\sim 10^8$ stars within

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1 kpc. Nevertheless we set out in this paper to make a first attempt at identifying candidate siblings of the Sun by searching in the Hipparcos Catalogue and adding complementary data from the Geneva-Copenhagen survey of the Solar neighbourhood (Holmberg et al. 2009). Our motivation is to carry out a first exploration of kinematic searches for the Sun's siblings. We describe our search methodology in section 2 and present our results in section 3. We discuss the results in section 4 and outline the steps needed to carry out a thorough future search for the Sun's siblings in section 5.

2 SEARCH METHODOLOGY

As shown in Portegies Zwart (2009) the Sun's siblings are expected to remain near the Sun's orbital trajectory and will form a characteristic pattern in the proper motion vs. distance plane. The specific distribution of the Sun's siblings in phase space can thus be used to find candidate siblings in the Solar neighbourhood. We pursue this idea by first simulating the orbits of the stars in the Sun's birth cluster, starting from the presumed birth place of the Sun. The latter is found by tracing back the Sun's orbit over 4600 Myr in an analytic Galactic potential. The birth cluster is then generated and the orbits of all the stars in the cluster integrated forward in time in order to find the present day phase space distribution of the siblings that remain near the Sun.

The simulated phase space distribution can be used to make a first selection of sibling candidates from the stars with known phase space data near the Sun. To do this we will use the Hipparcos Catalogue (ESA 1997), specifically the re-reduced version of the catalogue by van Leeuwen (2007). This first selection has to be narrowed down further by using the powerful constraints of the Sun's age and metallicity as described in section 3.1.

2.1 Simulations

For this exploratory attempt at identifying candidate siblings of the Sun we decided to keep the simulations of the Sun's birth cluster simple. The birth cluster is simulated as a collection of stars with a Gaussian distribution in position and velocity:

$$\rho(r) \propto e^{-r^2/2\sigma_r^2} \quad \text{and} \quad f(v) \propto e^{-v^2/2\sigma_v^2}\,, \tag{1}$$

where $r = |\mathbf{r} - \mathbf{r}_\odot(0)|$ and $v = |\mathbf{v} - \mathbf{v}_\odot(0)|$ are the position and velocity of the cluster stars with respect to the Sun's position and velocity at birth (at time $t = 0$). The dispersions σ_r and σ_v are in units of pc and km s^{-1}. The self-gravity of the cluster stars is ignored in these simulations (the stars are all treated as test particles in the Galactic potential) which amounts to assuming that the cluster rapidly disperses after its formation. As shown by Portegies Zwart (2009) this is actually the most challenging case as then only about 10% of the siblings are expected to be found within 1 kpc from the Sun at present. The clusters were simulated with the following dispersions in position and velocity: $\sigma_r = 1$, 3 pc and $\sigma_v = 0.5$, 1, 2 km s^{-1}. These numbers span plausible birth cluster sizes and velocity dispersions (cf. Portegies Zwart 2009; Adams 2010) and are consistent with the assumed number of cluster stars. This can be shown by assuming a Salpeter (1955) IMF for a cluster of 3000 stars with a mass range of 0.1–50 $M_\odot$, which implies a total cluster mass of $\sim$ 1000 $M_\odot$. The virial theorem can then be used to make a crude estimate of the velocity dispersion of the cluster $\sigma_v^2 \approx GM/\sigma_r$, which for cluster masses of a few 100 (for non-Salpeter IMFs) to 1000 $M_\odot$ leads to values for σ_v in the range $\sim$ 0.7–2 km s^{-1}. All combinations of the σ_r and σ_v values listed above were used. Although the real birth cluster is expected to have contained a few thousand stars, 10 000 stars were simulated in each cluster in order to sample the present day phase space distribution with sufficient resolution.

The birth position of the Sun is found by integrating its orbit backward in time, starting from the current position and velocity of the Sun. The present day position of the Sun is fixed at $(X, Y, Z)_\odot = (-8.5, 0, 0)$ kpc in the conventional Galactocentric Cartesian coordinate system.[1] The Sun's present day velocity with respect to the local standard of rest was taken from Aumer & Binney (2009) to be $(U, V, W)_\odot = (9.96, 5.25, 7.07)$ km s^{-1}. Recently Binney (2010) and McMillan & Binney (2010) advocated an upward revision of $V_\odot$ to 11 km s^{-1} and this value was also used to trace back the Sun's birth position. For both starting positions in velocity space all the cluster configurations mentioned above were simulated.

All orbit integrations were carried out in the analytic potential described in Allen & Santillán (1991), which consists of a Miyamoto-Nagai disk, a Plummer bulge, and a spherical halo (in this potential the circular velocity at $R = 8.5$ kpc is 220 km s^{-1}). We used a 7th order Runge-Kutta integrator RK7(8) with the coefficients listed in Fehlberg (1967). The integration time was fixed to 4600 Myr for both the backward integration of the Sun and the subsequent forward integration of the cluster stars. For the near-circular orbits integrated in these simulations the energy conservation error is always at the machine precision level.

Figure 1 shows the present-day distribution of the Sun's siblings projected on the Galactic plane for four of the birth cluster parameters mentioned above. The main message in this figure is that the distribution of the Sun's siblings is mainly sensitive to the velocity dispersion of the birth cluster. The initial size plays almost no role and the value of the Sun's V velocity mainly influences the birth position and velocity but does not have an effect on the final distribution in space of the siblings. The value of $V_\odot$ does have an effect on the velocity distribution of the siblings as will be discussed below. From here on we will only consider birth clusters with $\sigma_r = 1$ pc.

3 SELECTING CANDIDATE SIBLINGS FROM THE HIPPARCOS CATALOGUE

As pointed out in the introduction the $\sim$ 100–1000 siblings within 1 kpc from the present day position of the Sun will have to be identified from among the $\sim 10^8$ mainly Galactic disk stars in the same volume. It will thus be important to find a corner of phase space where there is a high contrast between the siblings and the Galactic background. Following Portegies Zwart (2009) we start by examining the distribution of stars in the distance vs. proper motion plane, which is shown in Fig. 2. The contours in this figure show the distribution of the Hipparcos Catalogue stars in proper motion vs. parallax. The overall shape of this distribution reflects the local Galactic disk kinematics combined with the Hipparcos completeness limits. The overall trend of proper motion with parallax is intrinsic to the Galactic disk. We verified this by generating a mock all-sky catalogue of stars, complete to $V = 12$, using the Besançon

[1] Translated to a Sun-centred reference frame the X-axis points toward the Galactic centre, the Y-axis in the direction of Galactic rotation, and the Z-axis completes the right-handed coordinate system.

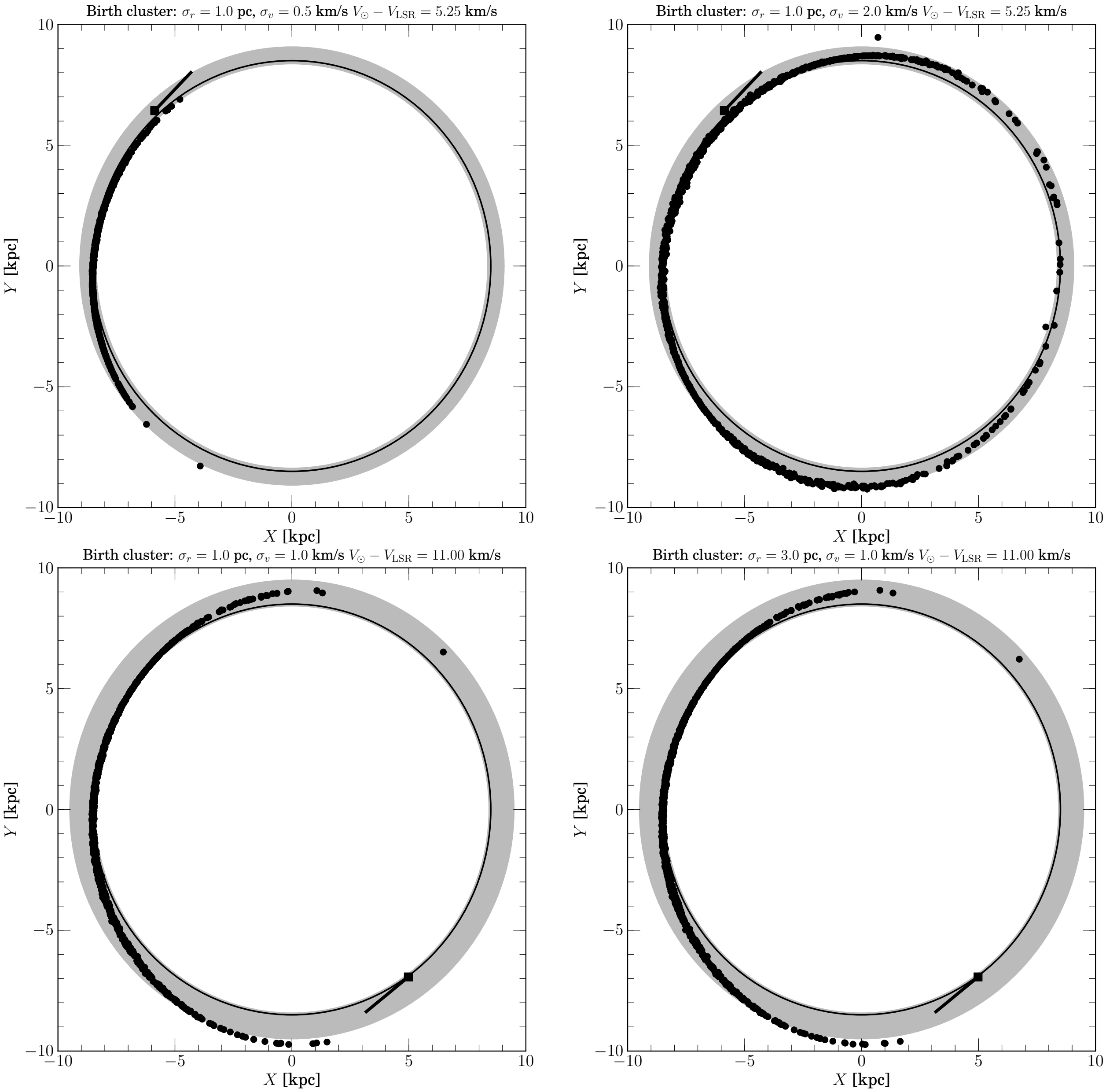

Figure 1. Distribution of the Sun's siblings projected on the Galactic plane for various birth cluster parameters. In all panels the grey ring indicates the radial extent of the Sun's orbit over the past 4600 Myr and the large dots show the present-day distribution of the siblings. Only one in every ten siblings is plotted. In the top two panels the present day value of $V_\odot$ is 5.25 km s^{-1} and in the bottom two panels the value is 11 km s^{-1}. Note the difference in the solar orbit and its birth position and velocity (indicated by the large square with the velocity vector attached). The top two panels illustrate the effect of increasing the birth cluster velocity dispersion from 0.5 (left) to 2.0 km s^{-1} (right); the siblings are spread much more along the Sun's orbit in the latter case. The bottom panels illustrate that the results are not sensitive to the size of the cluster which is $\sigma_r = 1$ pc in the left panel and $\sigma_r = 3$ pc in the right panel. In all panels the large black circle indicates the orbit of the LSR in the Allen & Santillán (1991) potential.

model (Robin et al. 2003, 2004).[2] The lack of stars at proper motions below 1 mas/yr and parallaxes below a few mas is due to the incompleteness of the Hipparcos Catalogue beyond $V \sim 8$ (cf. ESA 1997). Important in this discussion is that the lack of stars at low proper motion and high parallax is not caused by a selection bias.

We now examine the simulated distribution of the Sun's siblings in the proper motion vs. parallax plane, indicated by the large dots in Fig. 2. The simulated distributions are shown for low and high velocity dispersion of the birth cluster and for the low and high values of the V velocity of the Sun. In all cases the proper motions converge to a value of about 5–6 mas/yr at small parallaxes (large distance). This can be understood by considering stars that are moving along the solar circle with a velocity comparable to that of the Sun. Their proper motion will at large distance converge to $\sim V_{\rm LSR}/(4.74R_\odot)$. In fact at large distances the upper and lower limit on the proper motion are given roughly by $\mu \sim (V_{\rm LSR} \pm V_\odot)/(4.74R_\odot)$, where $R_\odot$ is the distance from the Sun to the Galactic centre and $V_{\rm LSR}$ is the velocity of the local

[2] The model can be run at `http://model.obs-besancon.fr`.

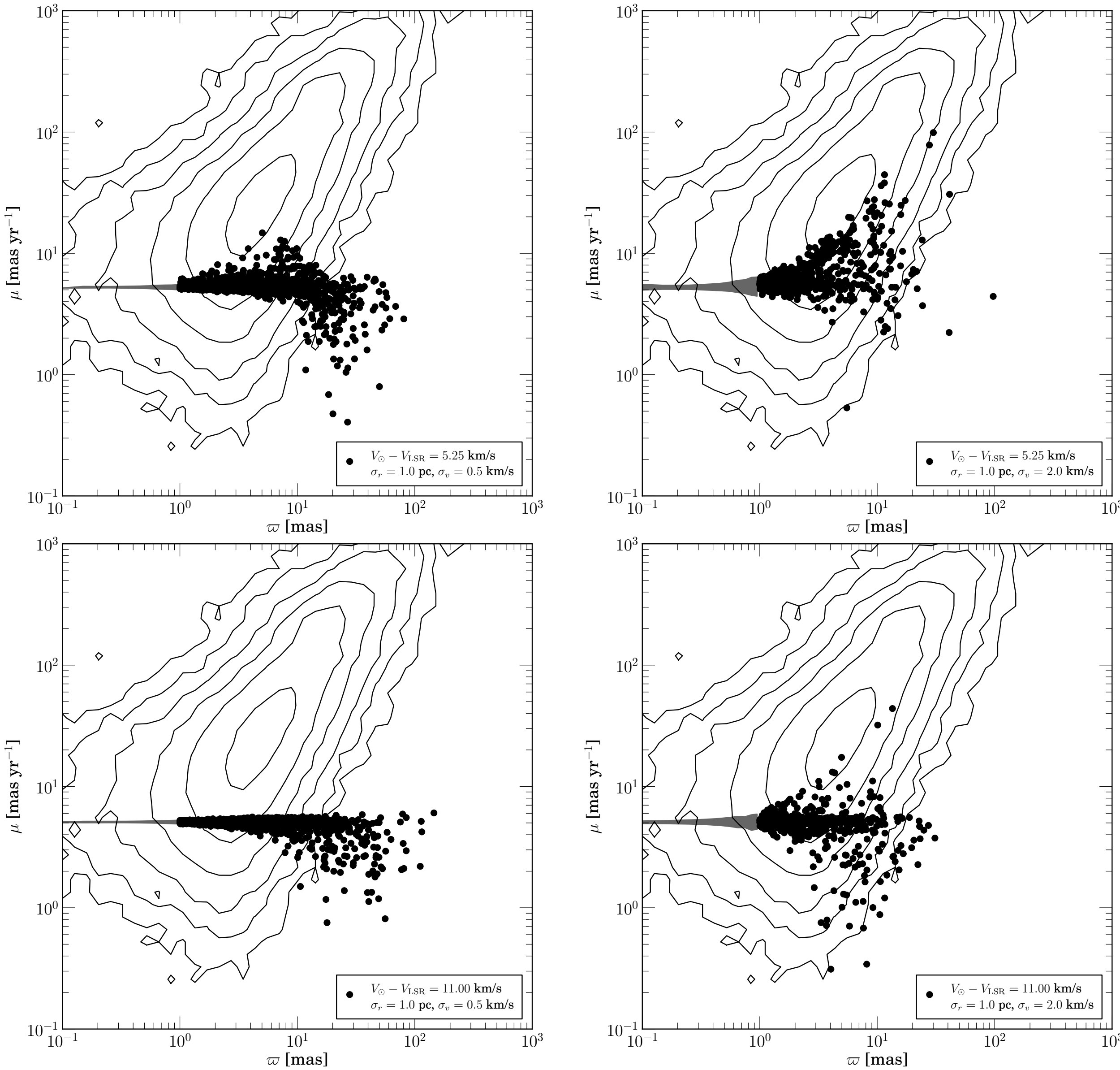

Figure 2. Distribution of the Sun's siblings in the proper motion (μ) vs. parallax (ϖ) plane. In all panels the distribution of Hipparcos Catalogue stars in this plane is shown as the contours, which indicate the numbers of stars in bins of 0.1×0.1 dex^2. The contour levels are at 3, 10, 30, 100, 300, and 1000 stars/bin. The dots show the simulated distribution of the siblings for low (left panels) and high velocity dispersion of the birth cluster, and for the low (top panels) and high (bottom panels) value of the V component of the Sun's present day velocity. At $\varpi \leqslant 1$ mas the distribution of the siblings is indicated with the grey region showing the mean proper motion ± 3 times the standard deviation in the distribution.

standard of rest. The ratio $(V_{\rm LSR} + V_\odot)/R_\odot$ was constrained by McMillan & Binney (2010), from observations of Galactic maser distances and motions, to lie in the range 29.8–31.5 km s^{-1}kpc^{-1}, which expressed as a proper motion is 6.3–6.6 mas/yr. At close distances (large parallaxes) the siblings can exhibit both higher and lower proper motions, where the upper and lower limits on the proper motion value can again be roughly obtained by considering stars on the same (nearly circular) orbit as the Sun and taking the varying distance into account. Proper motions larger than $\sim$ 5–6 mas/yr only occur if σ_v is relatively large compared to $V_\odot$ ($\sigma_v/V_\odot \gtrsim 0.1$ judging from Fig. 2). However, in all cases shown in Fig. 2 there is a group of siblings at low proper motion and high parallax, occupying the part of the diagram where few disk stars are expected. As a first selection of candidate siblings of the Sun we therefore choose the sample of Hipparcos stars with:

$$\varpi \geqslant 10 \text{ mas} \wedge \sigma_\varpi/\varpi \leqslant 0.1 \wedge \mu \leqslant 6.5 \text{ mas/yr}, \qquad (2)$$

where we additionally select on the parallax precision. We note that the siblings with these characteristics are predicted to have radial velocities of less than $\sim$ 10 km s^{-1} in absolute value, where the distribution is rather strongly peaked around $v_{\rm rad} \sim 0$ km s^{-1}. In our selection (2) we make use of the observationally established value of $(V_{\rm LSR} + V_\odot)/R_\odot$ in order to avoid introducing biases related to inadequacies in the simulated phase space distribution of the siblings.

This first selection of candidate siblings is mainly a quantitative statement of the search for nearby stars on almost the same orbit as the Sun. The number of candidate siblings after this first cut is

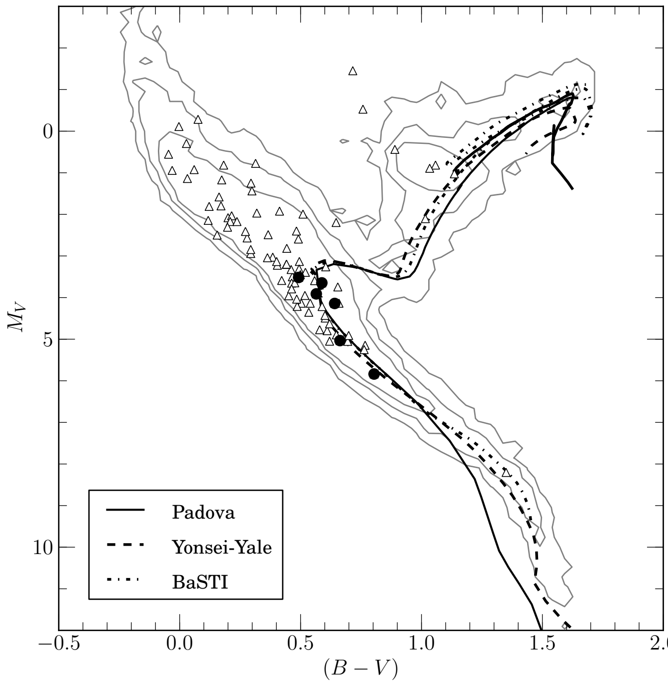

Figure 3. Colour magnitude diagram showing the absolute magnitude M_V vs. $(B-V)$. The contours show the distribution in this diagram of the stars in the Hipparcos Catalogue with $\sigma_\varpi/\varpi \leqslant 0.1$ and $\sigma_{(B-V)} \leqslant 0.05$ (data from van Leeuwen 2007). The contours show the numbers of stars in bins of 0.05×0.2 mag^2, where the contour levels are at 5, 20, 50, and 500 stars/bin. The triangles are the candidate siblings selected according to (2) and the large dots are the siblings selected from Holmberg et al. (2009) with ages consistent with that of the Sun (4.6 Gyr). The solid line shows the isochrone at the age and metallicity of the Sun according to the Padova models (Marigo et al. 2008), the dashed line shows the same isochrone for the Yonsei-Yale models (Demarque et al. 2004), and the dot-dashed line for the BaSTI (Pietrinferni et al. 2004) models.

87. In the following section we further examine these stars by cross matching them against the Geneva-Copenhagen survey (Holmberg et al. 2009) and considering their ages and metallicities.

3.1 Narrowing down the candidate list

In figure 3 we show the colour magnitude diagram for the candidate siblings selected according to (2). The absolute magnitudes M_V were calculated using the V-band magnitudes from the Hipparcos Catalogue (ESA 1997) and the parallaxes from the new reduction (van Leeuwen 2007). Only stars with precise parallaxes ($\sigma_\varpi/\varpi \leqslant 0.1$) and colours ($\sigma_{(B-V)} \leqslant 0.05$) were selected to produce the contours. The triangles in figure 3 are the candidate siblings selected according to (2). The figure also shows three isochrones at the age, 4.6 Gyr, and composition of the Sun according to the Padova (solid line, Marigo et al. 2008), Yonsei-Yale (dashed line, Demarque et al. 2004), and BaSTI (dot-dashed line, Pietrinferni et al. 2004) stellar models.

From the location of the isochrones it is clear that we can (not surprisingly) exclude stars with $(B-V) < 0.5$ as candidate siblings of the Sun, they are simply too young. Similarly the three giant stars at $0.5 < (B-V) < 1.0$ and $M_V < +1$ can be excluded as candidate siblings. The rest of the stars cannot be excluded as candidate siblings *on the basis of the information used so far*.

To further narrow down the list of candidate siblings we need to examine the ages and compositions of the remaining stars, ideally using spectroscopy to determine the astrophysical parameters of the stars and their chemical compositions. However as a first step we cross-correlated the list of Hipparcos selected candidate siblings against the data from the Geneva-Copenhagen survey (Holmberg et al. 2009, 2007; Nordström et al. 2004). We made use of the age estimates in this survey to make a further selection among the candidate siblings by demanding that the age is consistent with 4.6 Gyr to within the confidence limits quoted in Holmberg et al. (2009). This results in the 6 candidate siblings indicated by the dots in figure 3. We list the properties of these stars in Table 1. The masses for these stars are in the range 0.8–1.2 solar masses according to Nordström et al. (2004).

For two of the selected stars (HIP 30344 and 90112) the most likely ages are of the order of 1 Gyr and both of them have relatively high radial velocities, making it unlikely that they are siblings of the Sun. Of the four stars with ages similar to the Sun (all located near the turn-off point on the isochrones) there are two (80124 and 99689) that have somewhat low values of $[\mathrm{Fe/H}]$ and one (51581) which has $[\mathrm{Fe/H}] = 0$ but a rather high radial velocity. This leaves the star HIP 21158 as the most likely candidate to be a sibling of the Sun. However with a parallax of 26 mas its radial velocity is high compared to the predicted radial velocity of $\lesssim 2$ km s^{-1}.

We note that the 5 stars at $(B-V) > 1.0$ selected as candidate siblings from the Hipparcos Catalogue all lie near the solar age isochrone. These are HIP 56287, 57791, 89825, 92831, and 101911, of which none occurs in the Geneva-Copenhagen survey. The SIMBAD[3] database was used to find the values of $[\mathrm{Fe/H}]$ and v_{rad} for these stars. The first three are unlikely to be siblings on account of their radial velocities which are all larger than 10 km s^{-1}. The metallicity ($[\mathrm{Fe/H}] = -0.10$) and radial velocity (-8.7 km s^{-1}) for HIP 92831 ($(B-V) = 1.03$, $M_V = 0.9$) are consistent with being a sibling but no determination of its age exists. For HIP 101911 ($(B-V) = 1.02$, $M_V = 2.1$) no information was found on its radial velocity or $[\mathrm{Fe/H}]$ value.

4 DISCUSSION

Our search for siblings of the Sun in the Hipparcos Catalogue thus leaves us with at most 1 candidate sibling for which the radial velocity is on the high side (at least if the simulations from section 2.1 are to be trusted, see below). This is consistent with the fact that within 100 pc from the Sun only 0.1–1 sibling is expected according to the simulations done by Portegies Zwart (2009) for plausible numbers of stars in the Sun's birth cluster (Portegies Zwart 2009; Adams 2010).

For any reasonable cluster IMF it should be much more likely to find siblings of lower mass than the Sun rather than the slightly more massive candidates from table 1. However, our search for siblings has been based on data which is incomplete even for the nearest 100 pc to the Sun. This is mainly caused by the need for accurate trigonometric parallaxes which are used to place stars precisely in the colour-magnitude diagram before determining their ages. The Hipparcos catalogue is complete only to $V \sim 7$–8 (Turon & et al. 1992) which biases the sample of stars to those with masses above $\sim 1 M_\odot$. This selection effect is made stronger by the choice of sample for the Geneva-Copenhagen survey (cf. Nordström et al. 2004). The effect is to bias our present search to stars that are

[3] http://simbad.u-strasbg.fr/simbad/

Table 1. Observational properties of the candidate solar siblings selected from the Hipparcos and Geneva-Copenhagen Survey catalogues. The value of $[\mathrm{Fe/H}]$ and the ages are from Holmberg et al. (2009). The radial velocity was taken from Nordström et al. (2004).

HIP	$[\mathrm{Fe/H}]$	clAge^a Gyr	Age Gyr	chAge^b Gyr	$(B-V)$	M_V	v_{rad} km s^{-1}
21158	0.04	4.1	5.3	7.0	0.64	4.14	6.6
30344	−0.05		1.4	7.6	0.66	5.03	14.4
51581	0.00	3.4	3.8	5.4	0.59	3.65	17.4
80124	−0.27	3.6	4.2	6.0	0.56	3.91	−2.1
90112	−0.19		1.2	16.1	0.80	5.84	26.1
99689	−0.27	3.2	3.6	4.6	0.49	3.52	−4.4

^{a} Lower confidence limit on age.
^{b} Upper confidence limit on age.

brighter than the Sun. Of these stars the most numerous will be the ones near the main-sequence turn-off region for the solar age isochrone, which is where most of the candidates in table 1 are found.

We have restricted our search to the very nearby stars (within 100 pc) because of the higher contrast between possible siblings and field stars but also because the Geneva-Copenhagen survey is restricted to the nearest 40 pc around the Sun. This survey provides the most comprehensive (and readily available) set of consistent ages and metallicities for stars near the Sun and thus forms an important source of information in this study. Many more candidate siblings can be found at larger distances from the Sun and we did attempt to apply a different selection of sibling candidates. Siblings at distances between ~ 100 pc and ~ 1 kpc from the Sun are predicted in our simulations to cluster on the sky around the positions $(\ell, b) = (90^\circ, 0^\circ)$ and $(270^\circ, 0^\circ)$, which can be appreciated by examining figure 1. We thus selected candidate sibling in these regions of the sky from the Hipparcos catalogue and then further restricted the sample by selecting on parallax and proper motion using figure 2. This resulted in many candidates beyond the reach of the Geneva-Copenhagen survey and did not turn up additional candidates. Making use of other surveys that provide astrophysical information from spectroscopy, such as RAVE (Steinmetz & et al. 2006; Zwitter & et al. 2008) or SEGUE (Yanny & et al. 2009) is likely to be unsuccessful. In the case of RAVE the Galactic plane is not sufficiently covered and in the case of SEGUE the targets are too faint to appear in the Hipparcos Catalogue.

5 CONCLUSIONS AND FUTURE WORK

Motivated by the desire to find the remnants of the Sun's birth cluster we have conducted a preliminary search in the Hipparcos Catalogue for stars that could have been born in the same cluster. This search was based on the predicted phase space distribution of the Sun's siblings from simple simulations of the orbits of the cluster stars in a smooth Galactic potential. For nearby stars the simulations show that it is interesting to examine those that have small space motions relative to the Sun. From amongst the candidate siblings thus selected there are six stars with ages consistent with that of the Sun. Of these six candidate siblings 5 can be excluded on the basis of their radial velocity or metallicity, leaving only one plausible candidate sibling, HIP 21158. However, the latter still has a radial velocity somewhat higher than predicted from our simulations. This means we have not found a single convincing solar sibling within 100 pc from the Sun which is consistent with the predictions by Portegies Zwart (2009) and the fact that only a small fraction of the stars near the Sun was examined.

Now, even if a stronger case could have been made for the candidate siblings in table 1 based on their age and value of $[\mathrm{Fe/H}]$, this would not have proven that these stars are truly siblings of the Sun. We discuss below what steps need to be taken in future searches for the Sun's siblings.

The process of cluster disruption in the Galactic potential was simulated in a simplified manner in both this work and in Portegies Zwart (2009). A better understanding of the expected distribution of the siblings in phase space is essential for an efficient search for them in future large surveys. Hence it is important to do simulations of cluster disruption that are as realistic as possible. Effects to be included are the self-gravity of the cluster stars, non-axisymmetric structures in the Galactic potential, such as the bar and spiral arms, and the collisions of the cluster with molecular clouds in the Galaxy. The resulting phase space distribution is expected to be less orderly than depicted in figures 1 and 2 but to what extent is unknown at the moment. In these simulations it will be important to ensure that the resolution is comparable to realistic cluster and molecular cloud mass scales. To properly understand selection effects in surveys it is also necessary to include a realistic initial mass function and stellar evolution in the cluster simulations.

The observational challenge is equally daunting. On the one hand a large scale survey of phase space is needed, covering a large volume of the Galactic disk. Only the Gaia mission (Lindegren & et al. 2008) will provide this data at the precision needed to probe for siblings far away from the Sun. The above simulations will have to be exploited to develop efficient search methods that can weed out the candidate siblings from among the billion stars in the Gaia catalogue. However a search in phase space only is not sufficient as the stars from different clusters on similar orbits as the Sun's birth cluster could be confused with the genuine siblings. In addition it is known that clustering of stars in phase space can also be caused by dynamical effects (see for example, Antoja et al. 2009). The phase space search will have to be complemented by a very detailed astrophysical characterization of candidate siblings of the Sun. The age and overall abundance of the stars will not be enough in this respect as many clusters with abundances similar to the Sun's birth cluster may have formed around the same time. In addition the errors on individual stellar ages ($\sim$ 0.5–1 Gyr in table 1) are likely to remain larger than any plausible age spread within the birth cluster or

the lifetime of the molecular cloud from which the cluster formed. However, the Sun's siblings are expected to have the same detailed chemical composition as the Sun and true siblings can thus be identified through the analysis of high resolution spectra. The latter will have to be collected in a dedicated follow-up programme.

This 'chemical tagging' of stars has been proposed as a powerful method for associating them with their formation sites (Freeman & Bland-Hawthorn 2002). So far it has been demonstrated for the Hyades, the HR1614 moving group, and Cr 261 that these groups of stars indeed have unique chemical signatures and promising elements have been identified that can be used to chemically identify groups of stars (De Silva et al. 2007). However, a number of important studies regarding this technique remain to be done:

- No attempt has been made so far to *identify* (new) moving groups or clusters on the basis of abundance patterns, so the feasibility of this important aspect of the chemical tagging method remains to be demonstrated.
- It has not yet been definitively established to what accuracy the abundance patterns of stars have to be measured in order to identify them with their birth sites. Although De Silva et al. (2007) conclude that ~ 0.05 dex accuracy on individual abundance measurements may be enough to do so, it is not clear what accuracy is needed to distinguish formation sites at the same Galactic radius.
- If higher accuracy is needed differential abundance analyses offer the possibility of reaching ~ 0.01–0.02 dex accuracies as demonstrated by Meléndez et al. (2009) and Ramírez et al. (2009) for solar analogs. Can these accuracies also be reached over wider ranges in the effective temperatures of stars? As these two papers suggest, at this level of accuracy the abundance patterns in stars may be affected by the presence or absence of a planetary system. This would then have to be accounted for in the search for the Sun's siblings.

With the Gaia survey starting in a few years from now, the questions above will be actively pursued in order to ensure that precision Galactic archaeology can be done by combining the accurate distances and kinematics from Gaia with accurate abundances for large samples of stars throughout the Galaxy. The results will open up the exciting prospect of further unravelling the birth environment and life and times of the solar system through the identification of the Sun's lost siblings.

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